Theoretical perspectives in QCD

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Hadron Collider Physics Symposium

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Outline

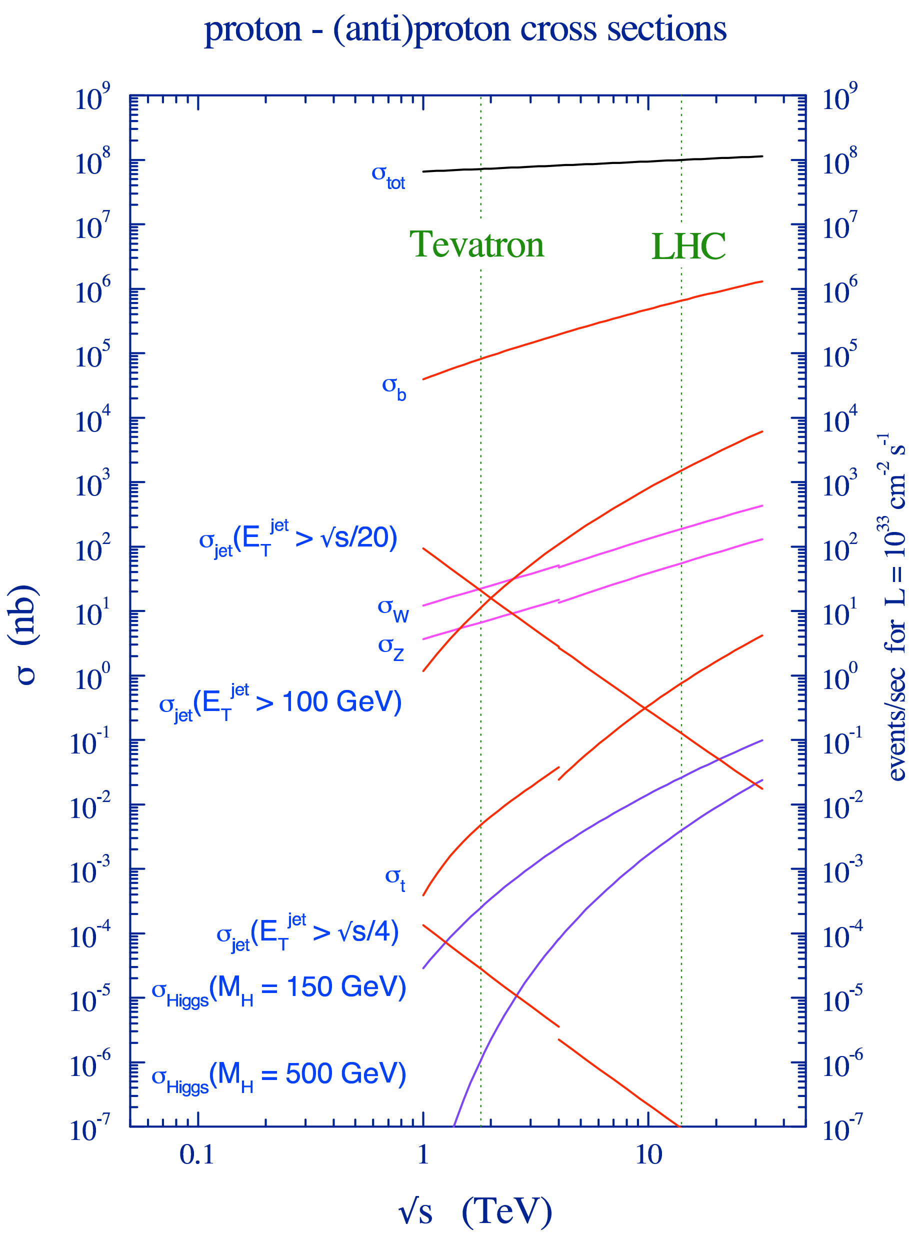
- Motivation
  - Limitations of parton shower Monte Carlos
  - Importance of perturbative QCD to verify and improve Monte Carlo tools
- Merging LO with parton showers
- Status of NLO calculations
  - $gg \to H \to WW$ at the LHC: NLO for discovery
  - Interplay between experimental cuts and higher order calculations
  - Automating NLO calculations
  - Merging NLO with parton showers
- Status of NNLO calculations
  - Parton distribution functions
  - W acceptances at NNLO with spin correlations
  - Higgs physics at NNLO: reweighting event generators and Higgs couplings

Physics at the LHC

- LHC turns on in ≈ 1 year!
- Excellent discovery reach at $\sqrt{s} = 14$ TeV:
  - SUSY: squark/gluino reach of 2.5-3 TeV
  - Z', graviton reach of 5-6 TeV
- Enormous event rates at $10\,\mathrm{fb}^{-1}$/year:
  - $W \to e\nu$: 10^8 events
  - $Z \to e^+e^-$: 10^7 events
  - $t\bar{t}$: 10^7 events
  - Higgs ($m_H = 700$ GeV): 10^4 events

$\Rightarrow$ Both an opportunity (precision, low systematics) and a challenge (backgrounds)

Signal excavation



- Not all discovery channels produce dramatic signatures!
- Need theoretical control of distribution shapes, backgrounds, uncertainties, . . .
- Measurements of new physics parameters needs theory
- Incorrect theory leads to:
  - Tevatron high E_T jets
  - Tevatron B-meson production
  - NuTeV $\sin^2\theta_W$
  - Brookhaven $g - 2$ of the muon

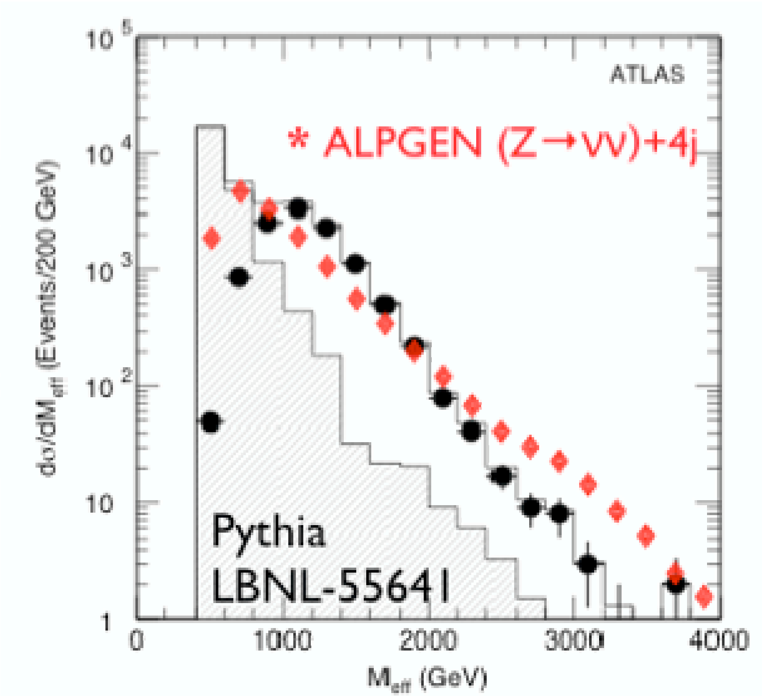
QCD tools for hadron colliders

- Develop, test QCD tools at HERA, Tevatron
- What are the possible approaches?
  - Fixed-order pQCD: systematic expansion in α_s $(\mathrm{LO}, \mathrm{NLO}, \mathrm{N^nLO})$
    - Quantify, reduce error by studying $\mu_{R,F}$ variation at each order
  - Analytic resummation: treat large logarithms to all orders in α_s
    $\Rightarrow \ln(m_H^2/p_T^2), \ln(1-m_H^2/\hat{s})$
  - Parton shower Monte Carlos (HERWIG, PYTHIA)
    - Generate many partons in collinear (leading log) approximation
    - Shower is universal; codes contain many processes

- HERWIG, PYTHIA: many partons allows hadronization, detector simulation; can access most physics processes; leading log resummation of dangerous kinematic regions
  $\Rightarrow$ default for many studies

How well do they do?

SUSY searches and PYTHIA

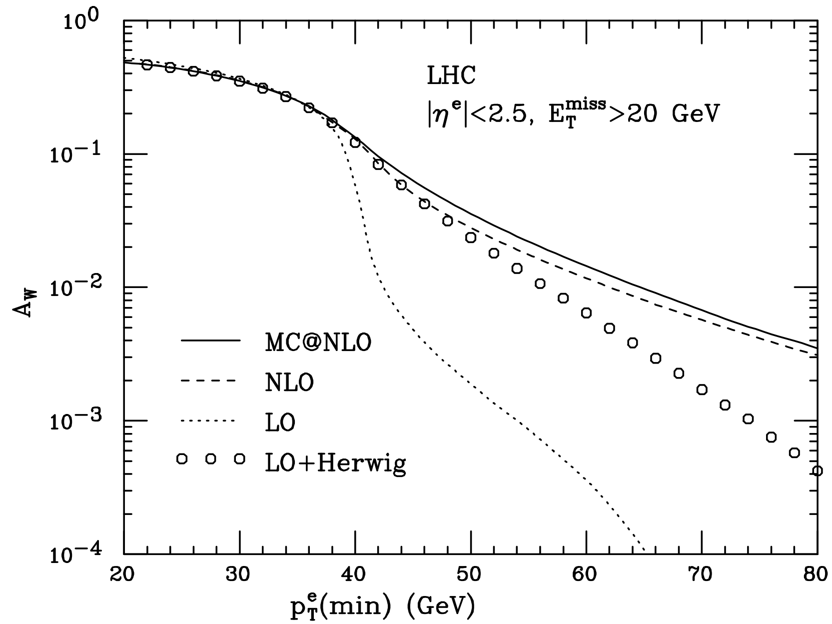


- $\mathrm{M_{eff}} = \sum_j p_\perp^j + E_\perp^{\mathrm{miss}}$: standard SUSY discriminator
- ALPGEN (Mangano et al.): exact LO matrix elements, correct hard emissions
- PYTHIA: extra jets generated via parton shower

$\Rightarrow$ PYTHIA does not describe multiple hard emissions well

W production and HERWIG

Frixione, Mangano



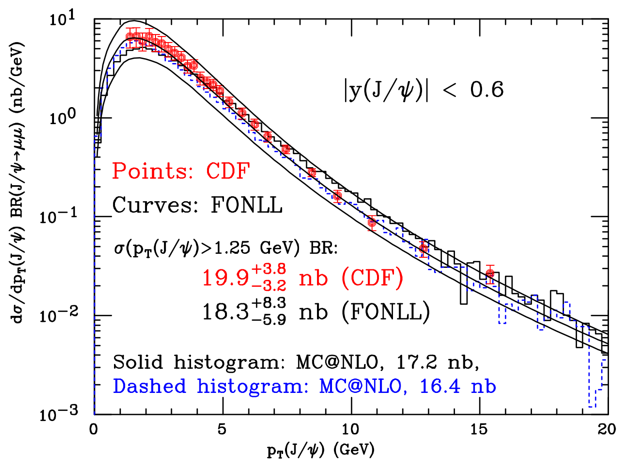
- $\frac{A_W[NLO]}{A_W[HERWIG]} \approx 2 - 10$ for $p^e_{T,min} \geq 50$ GeV
- Extra hard emission at NLO generates all events for $p^e_{T,min} > M_W/2$

$\Rightarrow$ HERWIG misses important effects for the W acceptance

Moral

- Moral: need systematic, controlled QCD expansion
  - pQCD expansion in α_s augmented with necessary resummation
  - Verify and improve Monte Carlo tools

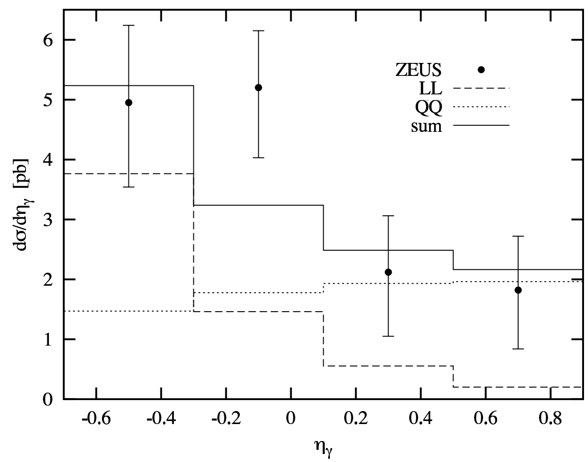
Cacciari et al.



B production at Tevatron

- Run I: data/theory ratio was 2-4
- Use consistent fragmentation extraction
- Resummation of $p_\perp/m_b$, new pdfs

Gehrmann et al.



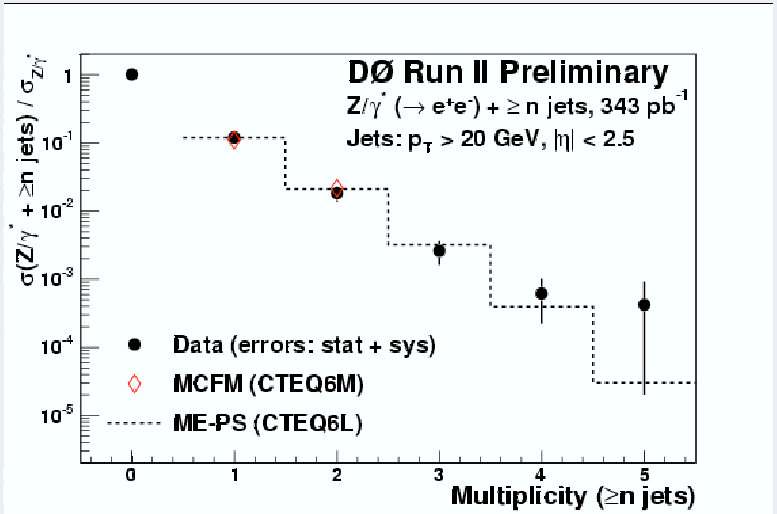
Isolated photons at ZEUS

- Data/PYTHIA=2.3, Data/HERWIG=7.9
- Both have incorrect kinematics
- PYTHIA γ from lepton, HERWIG γ from quark
- LO QCD gets rate and shapes correct

Merging LO with parton showers

- An N jet event: $N - m$ jets from parton shower, m from MEs, $m = 0, \ldots, N$
- MEs describe hard/large angle emissions, PS desribe soft/collinear
- CKKW (Catani, Krauss, Kuhn, Webber): prescription to cover entire phase-space correctly

Cross check on Run2 data



Includes up to $Zjjj$, $j = q, g$

Mrenna

- Generate $m < N$ hard jets; get m probability, kinematics from MEs
- Parton shower from this configuration; veto hard emissions
- Depends on parameter defining "hard" jet
- SHERPA: includes ME generator
- HERWIG, PYTHIA: use external tree-level generator, e.g. MADGRAPH and apply CKKW (Mrenna, Richardson)

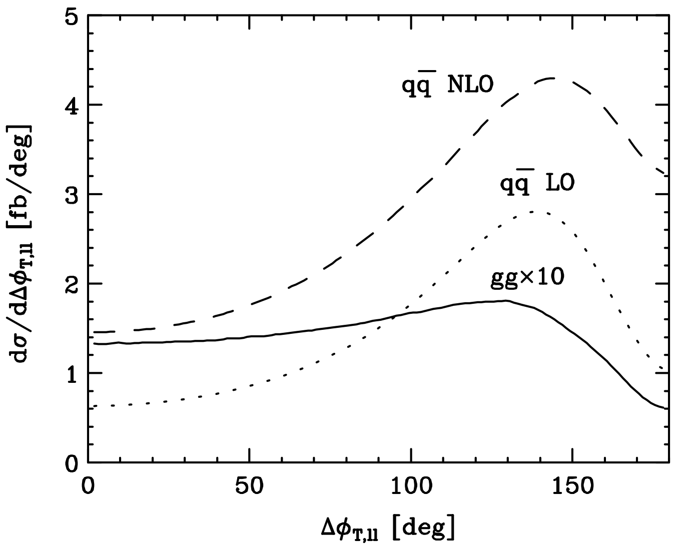
⇒ Describes Run II data well

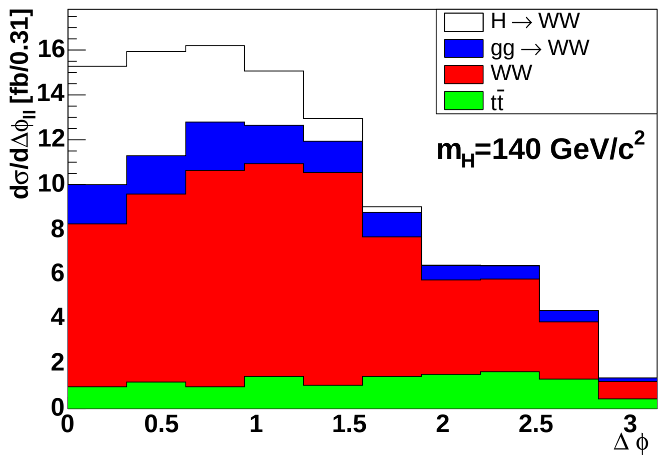
Status of NLO calculations

- Parton-level results available for all $2 \to 2$ and some $2 \to 3$ processes:
  - AYLEN/EMILIA (de Florian et al.): $pp \to (W,Z) + (W,Z,\gamma)$
  - DIPHOX (Aurenche et al.): $pp \to \gamma j, \gamma\gamma, \gamma^* p \to \gamma j$
  - HQQB (Dawson et al.): $pp \to t\bar{t}H, b\bar{b}H$
  - MCFM (Campbell, Ellis): $pp \to (W,Z) + (0,1,2)\,j,\ (W,Z) + b\bar{b}, V_1 V_2, \ldots$
  - NLOJET++ (Nagy): $pp \to (2,3)\,j$, $ep \to (3,4)\,j$, $\gamma^* p \to (2,3)\,j$
  - VBFNLO (Figy et al.): $pp \to (W,Z,H) + 2\,j$
  - $\ldots$
- Reduced theoretical uncertainty from $\mu_{R,F}$ dependence
- New qualitative effects, e.g., gluon pdf, p_T generation

Higgs discovery at higher orders

- NLO important for discovery
  - Important Higgs mode for $140 < m_H < 180$ GeV is $gg \to H \to WW \to l l \nu \nu$
  - Cannot reconstruct mass peak; rely upon kinematic distributions





  - NLO $pp \to WW$ background correction large: $\sigma_{NLO}/\sigma_{LO} > 1.5$
  - Loop-induced $gg \to WW$ formally NNLO; enhanced by $\Delta\phi_{T,ll} < 45^o$

$\Rightarrow$ further increases background by 30% (Binoth et al., Dührssen et al.)

NLO wishlist

Theoretical status

Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 2j$	$WW+\leq 0j$	$WWW+\leq 3j$	$t\bar{t}+\leq 0j$
$W+b\bar{b}+\leq 0j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 0j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 2j$	$ZZ+\leq 0j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 0j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 0j$
$Z+c\bar{c}+\leq 0j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 0j$
$\gamma+\leq 1j$	$\gamma\gamma+\leq 1j$		$b\bar{b}+\leq 0j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 0j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 0j$		
	$Z\gamma+\leq 0j$		

Campbell

- Want flexibile, automated approach $\Rightarrow$ many backgrounds, possible new states

Automating NLO calculations

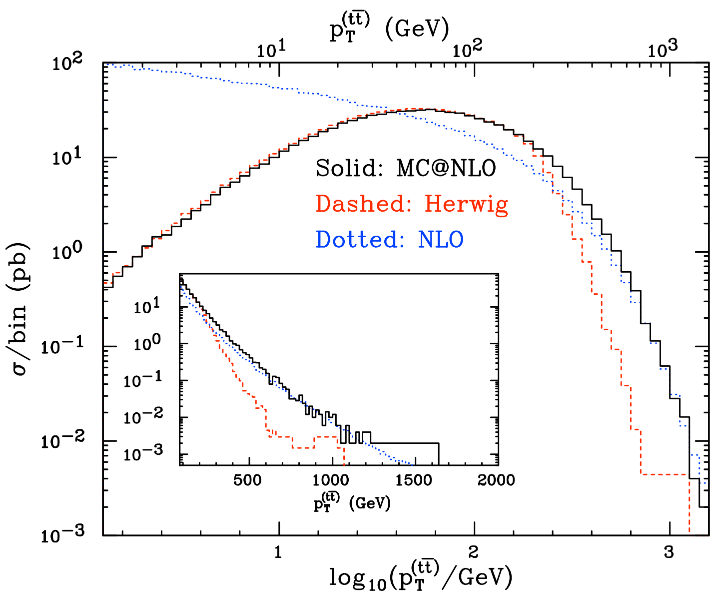
- Sticking point: loops for $n = 5, 6, \ldots$ external legs
  - Numerics complicated by soft, collinear singularities
  - Reduction to master integrals induces fictitious singularities
- Progress:
  - Expand reduction coefficients around fictitious singularities (Denner, Dittmaier)

  $\Rightarrow$ actually used to obtain EW corrections to $e^+e^- \to 4$ fermions
  - Semi-numerical (Ellis, Giele, Zanderighi): $\Rightarrow$ applying to Hjj
  - Twistor-inpsired (Berger, Bern, Dixon, Kosower; Britto, Cachazo, Feng; . . .)

$\Rightarrow$ lots of activity and new ideas!

Combining NLO with parton showers

- Fixed order, parton showers complimentary
  - PS: universal, leading log resummation, hadronization
  - FO: correct rates, hard emissions, reduced and quantifiable errors
  - ⇒ want the advantages of both approaches!



- MC@NLO (Frixione, Webber)
- Smoothly matches soft/collinear (MC) and hard (NLO) regions
- Unweighted events, NLO normalization
- Available for $W, Z, H, \gamma^*, b\bar{b}, t\bar{t}, WW, ZZ, WZ, tb$

- Activity! (Nagy, Soper; Giele, Kosower, Skands; Bauer, Schwartz)

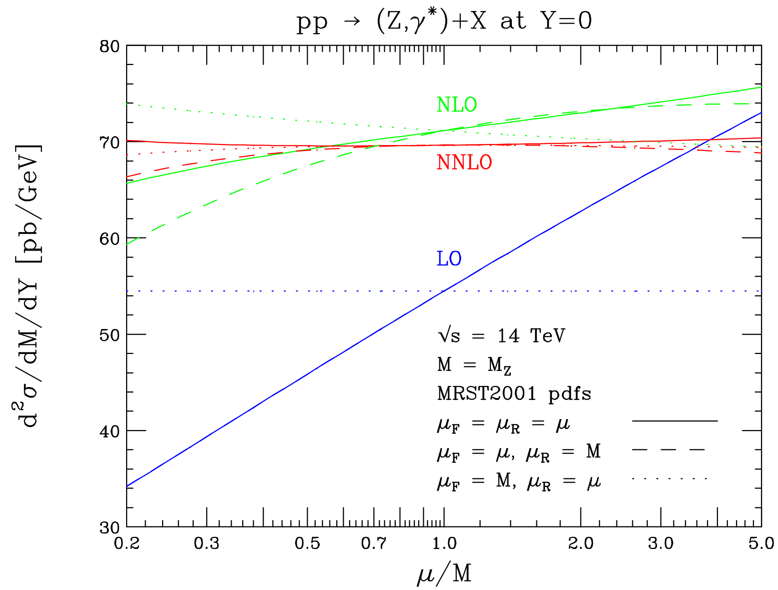
Status of NNLO calculations

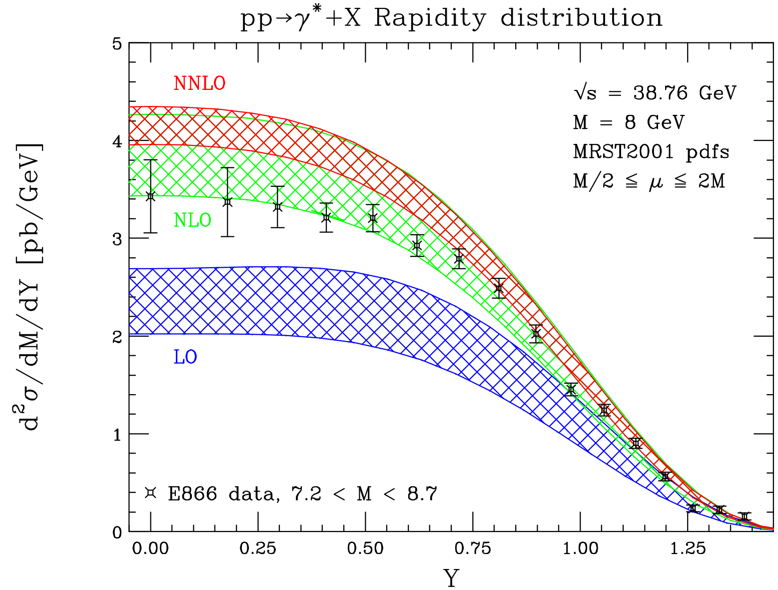
- When is NNLO needed?
  - When corrections are large (H production, fixed target energies)
  - For benchmark measurements, where expected errors are small ($W, Z, t\bar{t}$ production)
- What is known?
  - Several inclusive $2 \to 1$ processes (W, Z, H production)
    (van Neerven, Harlander, Kilgore, Anastasiou, Melnikov, Ravindran, Smith)
  - A few "semi-inclusive" $2 \to 1$ distributions (W, Z rapidity distributions)
    (Anastasiou, Dixon, Melnikov, FP)
  - Fully differential $2 \to 1$ result ($pp \to H, W, Z + X$)
    (Anastasiou, Melnikov, FP)
  - DGLAP splitting kernels (Moch, Vermaseran, Vogt)
  - Various approximate results (soft approximations)

$\Rightarrow$ Lots of activity and new ideas!

Drell-Yan rapidity distributions

- $\frac{d\sigma}{dY} \sim f_q(x_1) f_{\bar{q}}(x_2)$, $x_{1,2} = \sqrt{\frac{M^2}{s}} e^{\pm Y}$ $\Rightarrow$ need Y to fix pdf kinematics





Anastasiou, Dixon, Melnikov, FP

- Scale variation <1% after NNLO corrections at high Q^2
- Fixed-target indicates importance of NNLO corrections
- Sensitivity to different pdf extractions (Alekhin, MRST)
- DGLAP kernels of Moch et al., allow complete NNLO extraction of pdfs with DIS, DY

PDF improvements

- Currently NNLO extractions by Alekhin, MRST
  - Alekhin uses only DIS, MRST uses DIS, DY, jets
  - Current PDF uncertainties in W, Z from Alekhin (MRST similar):

    TEV: $\delta\sigma_W \approx 1.5\%$, $\delta\sigma_Z \approx 1.3\%$
    LHC: $\delta\sigma_W \approx 2.7\%$, $\delta\sigma_Z \approx 2.6\%$
  - However: MRST, Alekhin consistent when MRST restricts to same DIS sets

  $\Rightarrow$ "benchmark" MRST not consistent with the global MRST fit
  - Inconsistent data? Poor initial parameterization? Non-universal power corrections?
- Prospects: (HERA-LHC workshop, hep-ph/0511119)
  - HERA II: add jet data, projected $\approx 10\%$ improvement in sea quarks, high-x gluon
  - Neural network PDF fitting: remove bias from inital parameterization (del Debbio et al.)
  - NNLO description of both DIS, DY in fits?

Luminosity monitoring

- Monitor luminosity with W production (Dittmar et al.)
  - Reduce luminosity uncertainty to 1-5% level
  - Tevatron analysis as proof of principle?
  - Fullly differential NNLO calculation with spin correlations complete (Melnikov, FP)

  $\Rightarrow$ allows percent-level predictions for acceptance
  - Cut 1: $p_T^e > 20$ GeV, $|\eta^e| < 2.5$, $\not{E}_T > 20$ GeV (LHC)

    Cut 2: $p_T^e > 40$ GeV, $|\eta^e| < 2.5$, $\not{E}_T > 20$ GeV (LHC)

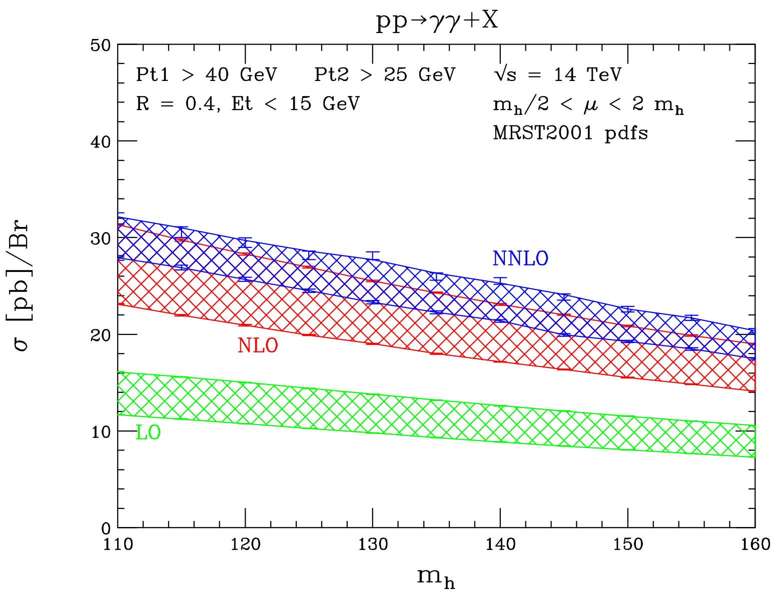
LHC	A(MC@NLO)	$\frac{\sigma_{MC@NLO}}{\sigma_{NLO}}$	A(NNLO)	$\frac{\sigma_{NNLO}}{\sigma_{NLO}}$
Cut 1	0.485	1.02	0.492	0.983
Cut 2	0.133	1.03	0.155	1.21

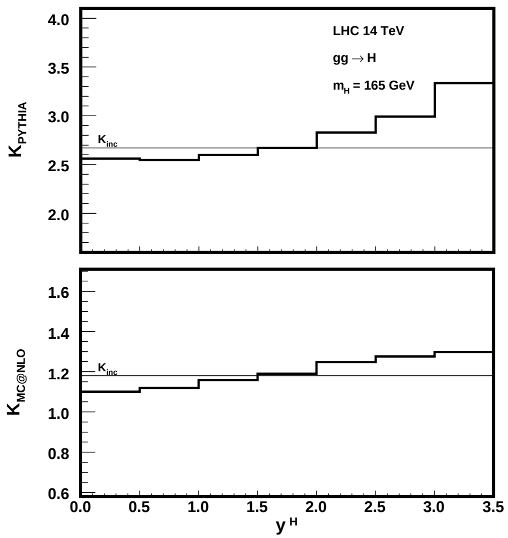
  - Large dependence of NNLO corrections on cuts, MC@NLO off by 20%
  - Plausibility: LO+parton shower (HERWIG) underestimates NLO

  $\Rightarrow$ extra hard emission at NNLO important!

Exclusive Higgs production

- Fully differential NNLO Higgs production calculation complete (Anastasiou, Melnikov, FP)
  - Allows predictions with *all* experimental cuts included
  - Inclusive K-factor is $\approx 2 \Rightarrow$ do cuts change this?
  - Important for measurements of Higgs couplings





Davatz et al.

- $\gamma\gamma$: effect of cuts $\approx 5\%$; WW: jet-veto is $\approx 20\%$ effect!
- Reweight MC output with differential K-factor to include kinematic dependences

Higgs coupling extractions

- Analyses of Higgs couplings use relation

$$\sigma(H) \times BR(H \to xx) = \frac{\sigma(H)^{TH}}{\Gamma_p^{TH}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma}$$

$\Rightarrow$ calculate and assign theoretical uncertainty to σ/Γ, extract $\Gamma_p \Gamma_x/\Gamma$ $\Rightarrow$ new states in loops should drop out from theory ratio, just QCD+PDFs

- Studies assign $\pm 20\%$ uncertainty to σ/Γ for $gg \to H$ production mode (Duhrssen et al.)

$$\Gamma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \left\{1 + \alpha(\mu_R) X_1 + \ldots\right\}$$
$$\sigma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \left\{1 + \alpha(\mu_R) Y_1 + \ldots\right\}$$

- Scale variation correlated, large μ_R variation cancels; $\Delta(\sigma/\Gamma) = \pm 5\%$
- **Recent work**:
  - $\mathrm{N^3LO}$ soft+virtual corrections to $\sigma_{gg \to H}$ (Moch, Vermaseran, Vogt)
  - $\mathrm{N^3LO}$ corrections to Γ_{gg} (Baikov, Chetyrkin)
  - $\Delta\sigma$: $\pm 10\% \to \pm 3 - 4\%$; $\Delta\Gamma$: $\pm 5\% \to \pm 1 - 2\%$
- Need inclusion of these effects in Higgs coupling studies!

Conclusions

- Need more work on QCD tools for LHC physics!
- Highlights:
  - Test of ME+PS merging on Tevatron Z+jets
  - $pp \to WW$ background shows importance of NLO signal, background calculations
    $\Rightarrow$ also interplay between higher orders and experimental cuts
  - Theory progress on automated NLO coming!
  - Many new techniques for $\mathrm{N^nLO}$ results for benchmark measurements
  - DGLAP kernels+Drell-Yan rapidity allows consistent NNLO PDF extraction
    $\Rightarrow$ new MRST fit, HERA jet data to shed light on discrepancies
  - Have differential W, Z result with spin correlations for acceptances
    $\Rightarrow$ Tevatron luminosity analysis?
- Intellectually vibrant, active fi eld
  - Progress from new ideas, not just turning the crank
  - Lots of new results in "old" physics!